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One Step Ahead Adaptive Control for Gas Turbine Power Plants

S. M. Camporeale[1], L. Dambrosio[2] and B. Fortunato[2]

[1]Dept. of Mechanics of Fluids and Offshore Engineering - University of Reggio Calabria
Contrada Feo di Vito - 89100 Reggio Calabria, Italy

[2]Istituto di Macchine ed Energetica - Polytechnic University of Bari
Via Re David 200 - 70100 Bari, Italy

ABSTRACT

The feasibility of the application of One Step Ahead Adaptive (OSAA) Control technique to a gas turbine power plant is investigated. The OSAA technique is a control algorithm especially suitable for non-linear and time-varying systems. This technique uses the Least Square algorithm to estimate in real-time a linear model of the controlled system, and, uses the estimated linear model to evaluate the feedback control variables.

The proposed technique allows to control the Gas Turbine power plant in a wide range of electric loads due to its intrinsic adaptive capabilities. Moreover, the OSAA control does not require the knowledge of the dynamic characteristics (e.g. state space systems or transfer functions) in order to design the control system.

The OSAA control system has been applied to a single shaft Gas Turbine power plant, which is numerically simulated. The proposed control technique has been tested both in Single-Input Single Output (SISO) mode and in Multi-Input Multi-Output (MIMO) mode. Starting from a steady-state condition, the power plant has been supposed to undergo a step reduction of the electric load. The results show that the OSAA control technique effectively counteracts the load reduction with limited overshoots in the controlled variables and, introducing a integral correction, a negligible static error.

INTRODUCTION

The dynamic behavior of Gas Turbine is inherently non-linear and characterized by a large number of internal parameters. Digital control systems presently include the simultaneous control of the rotational speed and of the combustion gas temperature in order to maximize the efficiency and control the exhaust emissions.

The design of the feedback characteristics of the control system generally requires a linearized model of the system in the s-space or in the state variable space (Camporeale and Fortunato, 1998).

The linearized model is obtained for a steady-state point and is generally applicable only in a limited range around such a steady state point. Typically the solution is based on the linearization of the system for various operating points and the controller gain parameters are found for these operating points using, e.g., linear quadratic regulator theory. These gain constants must be scheduled. as function of one or more engine state variables.

Non linear adaptive model are more suitable to describe the response of non-linear systems.

Some methods include a non-linear model of the system: such model is used in order to provide prediction of the behavior of the system for a better closed-loop control (Monopoli, 1981) or open-loop control (Vroemen and Essen, 1998).

For the gas turbine control applications, the control algorithms must be able to handle adequately the non-linearities but they should not require much computational time for real-time applications.

One of the most useful features of the *One-Step-Ahead* adaptive control technique is represented by its capability of self-tuning so that it can be applied to non linear and time variant system. Moreover it does not require an *a priori* knowledge of the controlled system (e.g. transfer functions). In principle, the *One-Step-Ahead* algorithm can be applied to a generic controlled system, just customizing few peculiar features. In previous works, two of the authors applied this technique to the control of wind systems (Dambrosio, 1995,

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Dambrosio and Fortunato, 1997; Dadone *et al.*, 1998; , Dambrosio and Fortunato, 1998)

In the following paragraphs, the One-Step-Ahead adaptive control technique is presented, and the specific features of the application to the control of a gas turbine power plant are described. The customized control technique is applied to regulate the gas turbine, which is numerically simulated. The first control study will consider the regulation of the output shaft rotational speed of the gas turbine connected to the electric generator in presence of abrupt changes of the load torque. A second control study will analyze the simultaneous control of the rotational speed and of the exhaust gas temperature, in presence of rapid changes of the electrical load.

ONE-STEP-AHEAD ADAPTIVE CONTROL TECHNIQUE.

The general layout of the control system is shown in Fig. 1. The block "System" represents the gas turbine to be controlled. Such a block represents the physical system, which will be numerically simulated by means of an appropriate mathematical model. The block Parameter Estimator is an essential block of the One-Step-Ahead control system. On the basis of an appropriate time sequence of input and output data, the parameter estimator evaluates a suitable linear model of the system which will change at each considered time step. The block "Design Calculations" records the desired control targets, i.e., the desired time history of the system outputs. The block "Control Law" determines the appropriate system inputs on the basis of the actual system outputs and of a comparison between the target outputs (recorded by the design calculation block) and the data estimated by the parameter estimator block.

The target of the control system is to regulate the system outputs represented by the rotational speed and the turbine outlet temperature.

The One-Step-Ahead adaptive control technique (Goodwin and Sin, 1984; Bryson and Ho Yu-Chi, 1975) combines the parameter estimation algorithm with the control scheme. In the following paragraphs, it will be first shown how to estimate a linearized model of the gas turbine on the basis of the previous sequence of the inputs and outputs. The Least Squares Algorithm (LSA) will be used for an on-line estimation of the linearized model parameters. Then the control scheme will be applied to the linearized estimated model of the controlled system.

LEAST SQUARES PARAMETER ESTIMATION ALGORITHM.

The non-linear system can be generally represented in the state variable notations as:

$$\dot{X} = f(X,U), \qquad (1)$$

where :

X = n dimensional state vector = $[x^{(1)}, x^{(2)}, \ldots, x^{(n)}]^T$

U = m dimensional input vector ($m \le n$) = $[u^{(1)}, u^{(2)}, \ldots, u^{(m)}]^T$

f = n dimensional non linear function vector = $=[f^{(1)}, f^{(2)}, \ldots, f^{(n)}]^T$

The objective of the OSAA control procedure is to synthesize U such that m of the n plant state variables follow a prescribed variation in time. Accordingly, the OSAA control technique can be applied if the set of equations in (1) can be reduced to:

$$\dot{X}_m = g_m(X_m, U), \qquad (2)$$

where:

X_m = m dimensional state vector to be controlled;

g_m = m dimensional non linear vector.

Generally such a reduction can be acceptable for a gas turbine power plant if a suitable choice of the controlled variables is given. In the following part, we will assume such reduction to be applicable and the subscript m will be omitted.

The Taylor series expansion of Eq.(2), truncated at the first order, at the steady state point $X = 0,\ U = 0$, gives:

$$\dot{X} = C \cdot X + D \cdot U, \qquad (3)$$

where C and D are the jacobian matrices with:

$$C = \begin{bmatrix} \frac{\partial g^{(1)}}{\partial x^{(1)}} & \frac{\partial g^{(1)}}{\partial x^{(2)}} & \cdots & \frac{\partial g^{(1)}}{\partial x^{(m)}} \\ \frac{\partial g^{(2)}}{\partial x^{(1)}} & \frac{\partial g^{(2)}}{\partial x^{(2)}} & \cdots & \frac{\partial g^{(2)}}{\partial x^{(m)}} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial g^{(m)}}{\partial x^{(1)}} & \frac{\partial g^{(m)}}{\partial x^{(2)}} & \cdots & \frac{\partial g^{(m)}}{\partial x^{(m)}} \end{bmatrix},$$

$$D = \begin{bmatrix} \frac{\partial g^{(1)}}{\partial u^{(1)}} & \frac{\partial g^{(1)}}{\partial u^{(2)}} & \cdots & \frac{\partial g^{(1)}}{\partial u^{(m)}} \\ \frac{\partial g^{(2)}}{\partial u^{(1)}} & \frac{\partial g^{(2)}}{\partial u^{(2)}} & \cdots & \frac{\partial g^{(2)}}{\partial u^{(m)}} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial g^{(m)}}{\partial u^{(1)}} & \frac{\partial g^{(m)}}{\partial u^{(2)}} & \cdots & \frac{\partial g^{(m)}}{\partial u^{(m)}} \end{bmatrix} \qquad (4)$$

Assuming that the variables are sampled at the constant time interval Δt, the time derivatives at the left hand side of Eq. (3) can be approximated by forward finite differences, as:

$$X_i = A_{i-1} \cdot X_{i-1} + B_{i-1} \cdot U_{i-1}, \qquad (5)$$

where the subscripts i-1 and i refer to the variable values at time $t=(i-1)\Delta t$ and $t = i\,\Delta t$, respectively. The matrices A and B are related to the matrices C and D by:

$$A = C \cdot \Delta t + I\,, \quad B = D \cdot \Delta t \qquad (6)$$

where I is the identity matrix.

While in the classical control techniques, A and B are evaluated on the basis of the mathematical model of the controlled system, the present technique does not require a previous knowledge of such relations. On the contrary, the values of A and B are evaluated on the basis of the input and output data referred to an appropriate past time window.

The Least Squares Algorithm (LSA), in recursive form, provides an on-line parameter estimator of A and B. The main features of this method are the simplicity and the very high convergence rate. Eq. (5) can be rearranged as:

$$X_i = \Theta_{i-1} \cdot \Phi_{i-1}, \tag{6}$$

where:

$$\Theta_{i-1} = \left[A_{i-1} \quad B_{i-1}\right], \quad \Phi_{i-1} = \begin{bmatrix} X_{i-1} \\ U_{i-1} \end{bmatrix}. \tag{7}$$

The LSA, from the known terms X_i and Φ_{i-1}, give the appropriate relations to estimate the unknown terms Θ_{i-1}.

Considering, for a simplified notation, a SISO system in which x is the state variable and u is the input variable, the Eq. (5) becomes:

$$x_i = a x_{i-1} + b u_{i-1} \tag{8}$$

In order to determine the parameters a and b, the LSA takes into account a set of N samples of x and u:

$$\begin{aligned} x_{i-N+2} &= a x_{i-N+1} + b u_{i-N+1} \\ &\ldots\ldots\ldots\ldots \\ x_i &= a x_{i-1} + b u_{i-1} \end{aligned} \tag{9}$$

Then LSA minimizes the following sum of squared errors:

$$S = \sum_{j=i-N+1}^{i} \left(x_j^* - x_j\right)^2 \tag{10}$$

In matrix-like form, Eq.(9) can be rewritten:

$$Y_i = \chi_{i-1} \cdot \Theta_{i-1} \tag{11}$$

where:

$$Y_i = \begin{bmatrix} x_{i-N+2} \\ \ldots \\ x_i \end{bmatrix}$$

$$\chi_{i-1} = \begin{bmatrix} x_{i-N+1} & u_{i-N+1} \\ \ldots & \ldots \\ x_{i-1} & u_{i-1} \end{bmatrix} \quad \Theta_{i-1} = \begin{bmatrix} a \\ b \end{bmatrix} \tag{12}$$

It is possible to verify that the values of a and b which minimizes S are given by:

$$\Theta_{i-1} = \left[\chi^T \cdot \chi\right]_{i-1}^{-1} \cdot \chi_{i-1}^T \cdot Y_i \tag{13}$$

In order to reduce the numerical effort, the following recursive expression, which gives a reasonable estimation of Θ_{i-1}, is used:

$$\Theta_{i-1} = \Theta_{i-2} + \frac{P_{i-3}\ \phi_{i-2}}{1 + \phi_{i-2}^T\ P_{i-3}\ \phi_{i-2}} \cdot \left[x_{i-1} - \phi_{i-2}^T\ \Theta_{i-2}\right] \tag{14}$$

with:

$$P_{i-2} = P_{i-3} - \frac{P_{i-3}\ \phi_{i-2}\ \phi_{i-2}^T\ P_{i-3}}{1 + \phi_{i-2}^T\ P_{i-2}\ \phi_{i-2}} \tag{15}$$

where the covariance matrix P_{i-1} and the vector ϕ_{i-1} are defined by:

$$P_{i-1} = \left[\chi^T \cdot \chi\right]_{i-1}^{-1} \qquad \phi_{i-1} = \begin{bmatrix} x_{i-1} \\ u_{i-1} \end{bmatrix} \tag{16}$$

The Eqs.(8-16) represent the version of the LSA for a SISO system. The relation to be used for a MIMO system can be found in Goodwin and Sin (1984) and in Dambrosio (1995).

ONE-STEP-AHEAD CONTROL SCHEME

The target of the One-Step-Ahead adaptive control is to drive to zero the tracking error:

$$e_{i+1} = X_{i+1} - X_{i+1}^*, \tag{17}$$

where X_{i+1}^*, denotes the desired output at time $t+\Delta t$. The control system has to minimize the error tracking. Accordingly, the Eq. (5), applied to the time interval between t and $t+\Delta t$, can be expressed as:

$$X_{i+1}^* = A_i \cdot X_i + B_i \cdot U_i. \tag{18}$$

In the One-Step-Ahead adaptive control, the parameter matrices A_{i-1} and B_{i-1} are supposed to remain unchanged from the time $t-\Delta t$ to the time t, i.e.:

$$A_i \cong A_{i-1}, \quad B_i \cong B_{i-1}. \tag{19}$$

Since the matrices A_{i-1} and B_{i-1} are estimated by means of Eqs.(14-15), the only unknowns in Eq.(18) are represented by the control variables in the vector U_i:

$$U_i = B^{-1}{}_{i-1} \cdot \left(X^*{}_{i+1} - A_{i-1} \cdot X_i\right) \tag{20}$$

Eq. (20) provides the control laws, i.e., the input variables required to warrant that the state variables follow the desired time sequence X^*. Such a requirement is exactly satisfied by linear systems. For non linear systems, the previous requirement is only approximately fulfilled, being the error tracking dependent on the time step Δt. As a consequence the matrices A_{i-1} and B_{i-1} must be continuously updated at each time step.

Further features of the OSAA control

Before analyzing the results of the application of the OSAA control to the Gas Turbine computer simulation, it is useful to make some considerations about this adaptive control technique.

As far as the LSA is concerned, it estimates the unknown parameters Θ_{i-1}, by using Eq. (14-15). These formulae are represented in recursive form and therefore they need some initial values for the parameter estimation matrix Θ_0 and for the covariance matrices P^i. If no better guess is available, the starting values will be:

$$\begin{aligned} \Theta_0 &= 0 \\ P_0 &= k \cdot I \end{aligned} \tag{21}$$

where the value of k can be chosen according to the sensitivity of the controlled system with respect to the control variables. Therefore, for those systems with low sensitivity with respect to the control variable, it is opportune to choose a high value of k ($k=10^6$). On the other hand, if the controlled system is very sensitive to the variation of the control variables, then it is useful decrease the value of k in order to avoid system instabilities. In other words, k represents the convergence rate of the linearized estimated model, expressed by Eq.(6), to the non linear controlled system (Gas Turbine computer simulation). In this point of view, the LSA just described, features very fast convergence rates, but the algorithm gain reduces quickly when the covariance matrix P becomes small after a few iterations, usually 10 to 20. This means that the LSA converges very rapidly to the true parameters values, but it is not able to track the computer Gas Turbine simulation with the same rate, as the latter changes configuration in time. In order to avoid this problem, the scheme just shown has been slightly modified by resetting the covariance matrix P to its starting value, P_0, at various time instants (e.g. every 20 iterations). This resetting technique will maintain the algorithm gain at a high value and, therefore, the parameter estimator will be able to track the output error, keeping a fast convergence rate.

Another important feature of the OSAA control system is related with the risk that the control variables variations assume too large values. Therefore, in order to avoid the control variables to assume too large values, the determinant of the matrix B_i in Eq.(20) must be not smaller than a fixed minimum value. This becomes critical whenever there is a sudden change in the disturbance variables. In fact, during a sudden variation of the disturbance variables, large control errors may occur. These control errors produce a large control action which can reduce the stability the controlled system. A way to avoid this problem is to check that the terms on the principal diagonal of the B_i matrix do not become smaller than some fixed minimum value. On the other hand this can cause some small constant tracking errors that can be eliminated introducing an integral control action, as it will be described in the "Results" section.

APPLICATION TO THE GAS TURBINE POWER PLANT

Mathematical model of the gas turbine

The gas turbine is numerically simulated by a mathematical model previously developed by the authors (Camporeale and Fortunato,1998). The model is able to simulate the dynamic behavior of a gas turbine, including the cooling system of the turbine blades. A stage-by-stage turbine model is given, in order to accurately describe the cooled expansion and approximately estimate the thermal stress of the blades during the transients. The model can be applied either to simple cycle or regenerative gas turbines, because it includes a mathematical model of the regenerator. The main characteristics of the model are summarized in the following part of this section. Further details can be found in the cited reference .

The model has a modular form: the system is defined properly connecting different subsystems or modules. The compressor and the turbine stages are modeled as lumped elements not containing mass (actuator disks) and are described by algebraic (quasi-steady) equations. In order to take into account the volumes of inlet duct, compressor, turbine and diffuser, a plenum is placed at the connection of the components. Inside the plenum the speed variations are negligible and the pressure and the temperature are considered uniform. Denoting with 1 and 2 the inlet and outlet sections, respectively, the non-steady equations of mass and energy conservation, applied to the plenum having volume V_p, give:

$$V_p \cdot \frac{d\rho_2}{dt} = g_1 - g_2 \tag{22}$$

$$V_p \frac{d(\rho_2 e_2)}{dt} = g_1 h_1 - g_2 h_2 \tag{23}$$

where g is mass flow rate, ρ is the density, e is the internal energy and h is enthalpy.

The plenum placed at the compressor discharge is provided two or more outlets for the extraction of the cooling air. In that case the Eq.(22) and (23) are modified introducing more exiting streams.

The combustion chamber is modeled as a capacity of constant volume V_{cc} where the mixing and the combustion processes take place. The internal temperature T_{cc} is supposed equal to the logarithmic mean value between the inlet and the outlet temperatures. The hypotheses for the pressure losses and the flow speed are the same adopted for the plenum. The non-steady mass and energy conservation equations give:

Table 1 - Basic performance of the gas turbine

Overall pressure ratio	14.7
Turbine inlet temperature	1250 [K]
Turbine outlet temperature	807[K]
Rotational speed	3000 [rpm]
Power output	62.2[MW]
LHV efficiency	36 %

$$V_{cc}\frac{d\rho_{cc}}{dt}=g_1+g_b-g_2 \quad (24)$$

$$V_{cc}\frac{d(\rho_{cc}e_{cc})}{dt}= \quad (25)$$
$$=g_1h_1+g_b\cdot(h_b+LHV)-g_2h_2$$

where g_b is fuel mass flow rate and LHV is the fuel Lower Heating Value.

Denoting with I the overall inertia of the gas turbine and of the electric generator, the rotational speed (ω) is related to the shaft dynamic balance:

$$\frac{d\omega}{dt}=\frac{1}{I\,\omega}\left(P_T-P_C-P_F-P_E\right) \quad (26)$$

where P_T is the power produced by the turbine rows connected to the shaft, P_C is the power absorbed by the compressor rows connected to the shaft, P_E is the power absorbed by the electric generator and P_F is the power loss for friction and accessories.

The compressor is supposed to be provided with variable inlet guide vanes (VIGVs).

A simplified approach is adopted in order to estimate the variation of the air mass flow produced by the VIGVs:

$$g_a(r_{VIGV},\omega,\beta)=g_a(1,\omega,\beta)\cdot r_{VIGV} \quad (27)$$

where g_a is the air mass flow, β is the compressor pressure ratio and r_{VIGV} is the ratio of the effective air mass flow to air mass flow at the same rotational speed and pressure ratio with IGVs completely open (r_{VIGV}=1).

The fuel valve and the IGV positioner are both modeled as first-order actuators. The relation between the fuel mass flow g_b and the input signal u_1 is given by the first-order differential equation:

$$\tau\frac{dg_b}{dt}=(u_1-g_b) \quad (28)$$

where τ is the time constant of the fuel valve. A similar relation is used for the IGV positioner.

The gas turbine characteristics

A single-shaft heavy-duty gas turbine for gas-steam combined cycle application is numerically simulated. The main characteristics of the gas turbine are given in Table 1. The gas turbine, schematized in fig.2 , is composed of:

- a multistage axial compressor (C);
- a plenum (P1), placed at the an intermediate stage of the compressor, representing the point from which part of the compressed air is extracted for cooling the second stage of the turbine;
- a plenum (P2), representing the air collector placed at the compressor outlet, from which part of the compressed air is extracted for cooling the first stage of the turbine;
- a combustion chamber (CC);
- a multistage turbine (T) in which the first two stages are air-cooled and the other stages are adiabatic;
- a shaft connecting the compressor, the turbine and the electric generator.

The regulation of the fuel rate (g_b) and of the compressor inlet guide vanes (r_{VIGV}) is performed with the aim of controlling the turbine shaft rotational speed and the turbine outlet temperature.

The turbine shaft rotational speed (ω) needs to be controlled because the shaft is directly coupled with the electric power generator. The turbine outlet temperature (T_o) is controlled in order to keep high, as much as possible, the plant overall efficiency at part load conditions. In fact, at part load, the compressor inlet guide vanes can be partially closed in order to reduce the air mass flow and the power output, maintaining about constant the cycle efficiency.

The control of the turbine outlet temperature has been preferred to the control of the turbine inlet temperature because, generally, this option is preferred for the reliability of the heat exchanger used for exhaust gas heat recovery.

A block diagram of the OSAA control applied to the gas turbine power plant is sketched in Fig.3 .

RESULTS

The first results are concerning a SISO application in which the rotational speed is regulated by means of the fuel flow. In this case the input to the system is the signal given to the fuel-valve. The turbine temperature is not controlled and the position of the inlet-guide vanes is fixed at $r_{VIGV}=1$. The power plant has been simulated in the case of a step reduction of the electric load starting from a steady-state condition. A time step of 0.01 *s* has been considered for the numerical integration. The considered load reduction is about 25 % of the initial value at the time instant *5 s*.

In the simulation the OSAA control needs to be initialized at the chosen steady-state point, in order to provide suitable values of the matrices **A** and **B**. There is not a loss of generality in this procedure because it should be taken in mind that the OSAA control is to be applied in real time to a continuously monitored gas turbine.

The Fig.4 shows the estimated parameters *a* and *b* of Eq.(8). According to Eq.(21) the initial values assigned to *a* and *b* are both 0. It appears that, after few seconds, the LSA provides a reliable estimation of the parameters. After the load variation, the values of the parameters estimated by the LSA algorithm are changed, according with the modified characteristics of system. It should be observed that, although the linearized state space model does not represent the best description of the gas turbine, the adaptive capability of the technique provides the parameter estimation that minimize the error between the actual and the desired output value.

The time plots in Fig.5 show the rotational speed, the signal to the fuel valve, evaluated by the OSAA control unit, and the actual fuel flow provided to the combustion chamber. It appears that the OSAA control technique is able to effectively counteract the load reduction with a limited overshoots in the controlled variable. Although a good behavior is achieved with the OSAA control algorithm previously described, a steady state error persists after the load variation. In fact, as shown by Eq. (20), the control action determined by the *One-Step-Ahead* is proportional to the control error. This control action does not ensure the control tracking error to be asymptotically reduced to zero, especially if the terms on the principal diagonal of the B_t matrix are not allowed to become smaller than some fixed minimum value. In order to eliminate the steady state error, integral control action was introduced. Then, considering this SISO application,the Eq.(20) was modified to be :

$$u_i = b^{-1}{}_{i-1} \cdot \left[x^*{}_{i+1} - a_{i-1} \cdot x_i + G \cdot \sum_{j=0}^{i} (x^*{}_j - x_j) \right] \tag{29}$$

where G is an appropriate integral gain. In such a way it is possible to asymptotically reduce to zero the static control error. Fig.6 shows that using the integral correction given by Eq.(29), the static error has been eliminated.

The oscillations observed in the response of the system are caused by the excessive control effort obtained with the OSAA control given either by Eq.(20) or Eq.(29). This is the typical behavior of the OSAA control which tries to minimize the error given in Eq.(17). In order to limit the variations of the fuel flow, the range of the coefficient *b* has been limited. The results obtained in this case (Fig.7) show that the oscillations in the system response are eliminated.

The second application concerns the simultaneous control of the rotor speed and of the turbine outlet temperature. Typically this is obtained by mean of two closed loops of control (Camporeale and Fortunato, 1998): in the first loop the rotor speed is controlled by the fuel flow; in the second loop the turbine outlet temperature is controlled by means of the position of the compressor inlet guide vanes. The interaction given by the simultaneous control of two variables on a single system causes specific control problems. One solution is possible introducing de-coupling blocks which have feed-forward characteristics and are able to cancel the mutual interaction. However, due to the non-linear characteristics of the system, the transfer function that characterize the de-coupling blocks should be scheduled for the various operating points of the gas turbine.

The OSAA control, instead, de-coupling blocks are not needed, because it is able to continuously up-date the linearized system which approximates the behavior of the gas turbine.

In this case study, the power plant has been simulated assuming a step reduction of the electric load of 10% of the initial value starting from a steady-state condition. The integral correction has been incorporated in the OSAA control system, extending the scalar relation in Eq.(29) to a multivariable formulation.

The controlled and the input variables are plotted vs. time in Fig.8: it appears that the OSAA control system counteracts the load variation in few seconds. From these results, we can infer that the real-time adaptive evaluation of the coefficient of the matrices *A* and *B*, gives a simplified system model but suitable for controlling the gas turbine. Moreover, the mutual interaction of the simultaneous control of the rotational speed and of the exhaust gas temperature appears to be well compensated. In fact, as shown by Eq.(20), the OSAA controller, through the off-diagonal coefficients in the matrix *B*, takes into account the influence of the fuel flow on the exhaust temperature, and the influence of the IGV position on the rotational speed, simultaneously.

CONCLUSIONS

The OSAA control technique seems to be a suitable basis for real time control development. The proposed approach is based on a simplified state-space linear model combined with a least squares parameter estimation by means a recursive technique. This approach should not require excessive computational time for gas turbine applications.

The results given by computer simulation, have shown that the OSAA control technique is able to provide a suitable control of the gas turbine power plant under electric load variation.

In the tested MIMO application, the mutual interference of the multiple input and controlled variables has been effectively counteracted by the OSAA control by means of its intrinsic capability to on-line estimate the off-diagonal coefficients in linear model approximating the real system. Also the static error has been eliminated by means of an integral control incorporated in the OSAA control algorithm.

Although the OSAA control seems to require a minimum design effort, the control system requires to be analyzed in order to avoid that it performs worse than a traditional system. In some situations the OSAA may cause excessive control action for to bring the output to the desired value. In the tested cases the range of the input variables has been simply limited, even if the control law can be improved by means of the *Weighted One-Step-Ahead Adaptive* controller which aims to minimizes the error in the desired output and the input variables (Goodwin and Sin, 1984).

Further work should be done in order to investigate the behavior of the controlled system in other typical situations, such as start-up operation or applications where measurement noise is present.

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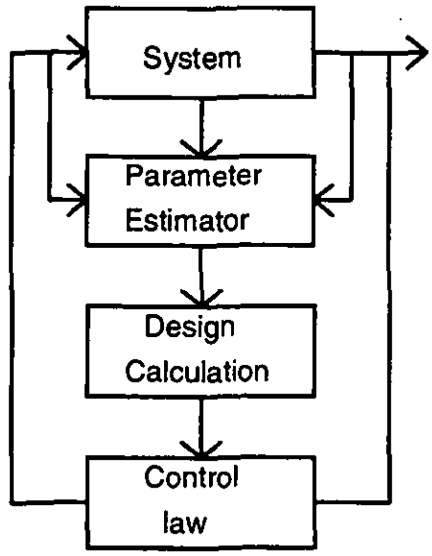


Fig.1 – Block diagram of the One-Step-Ahead control system

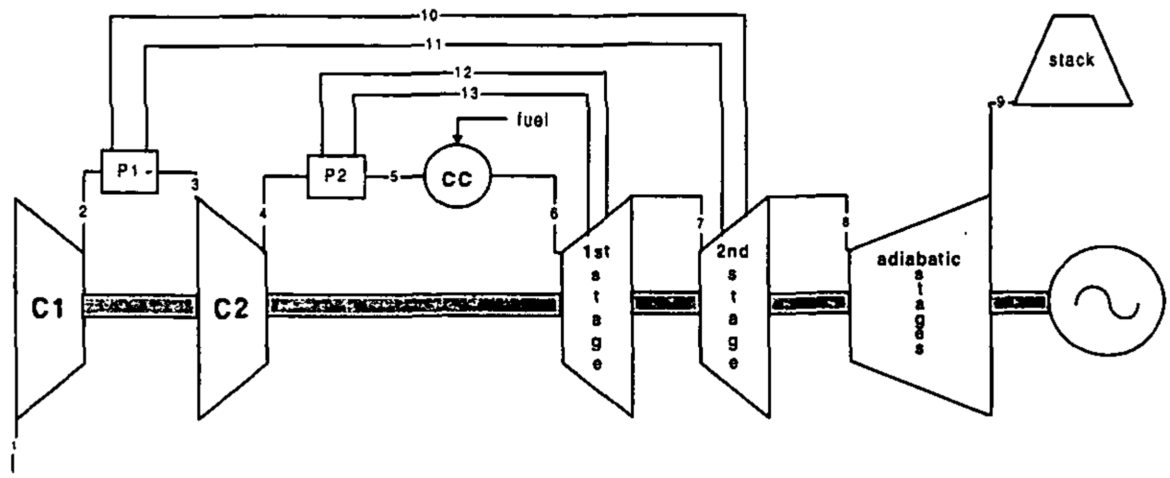


Fig. 2 – Modular scheme adopted for the numerical simulation of the gas turbine

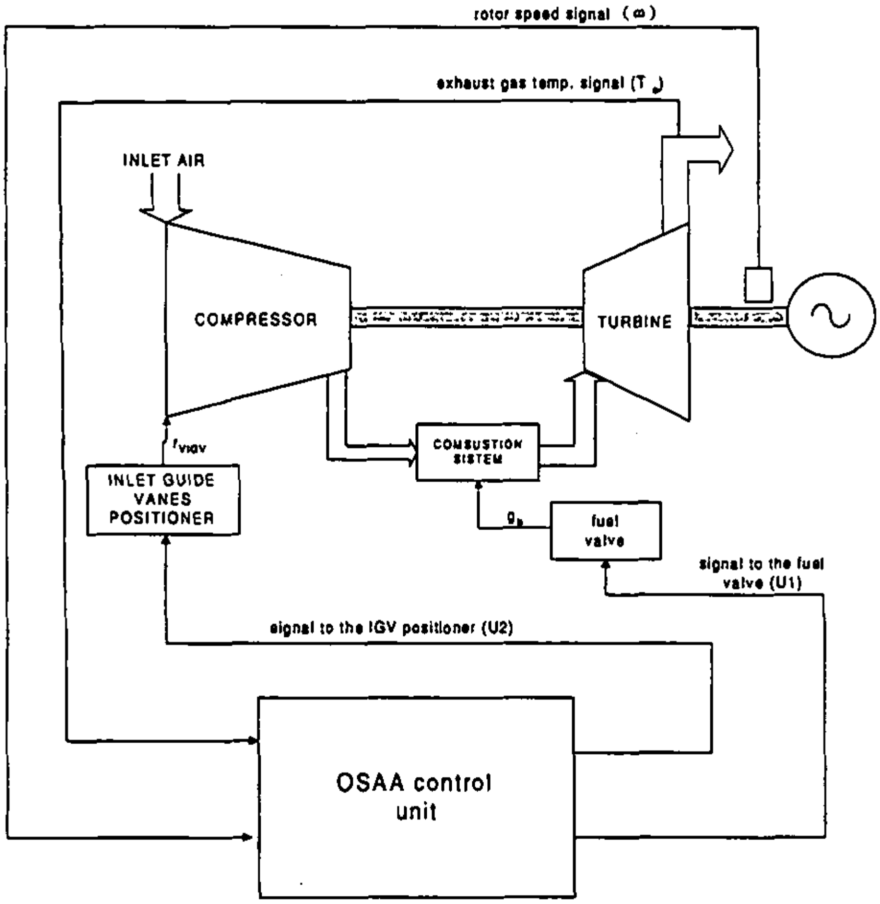


Fig. 3 – Block scheme representing the OSAA control system applied to the gas turbine

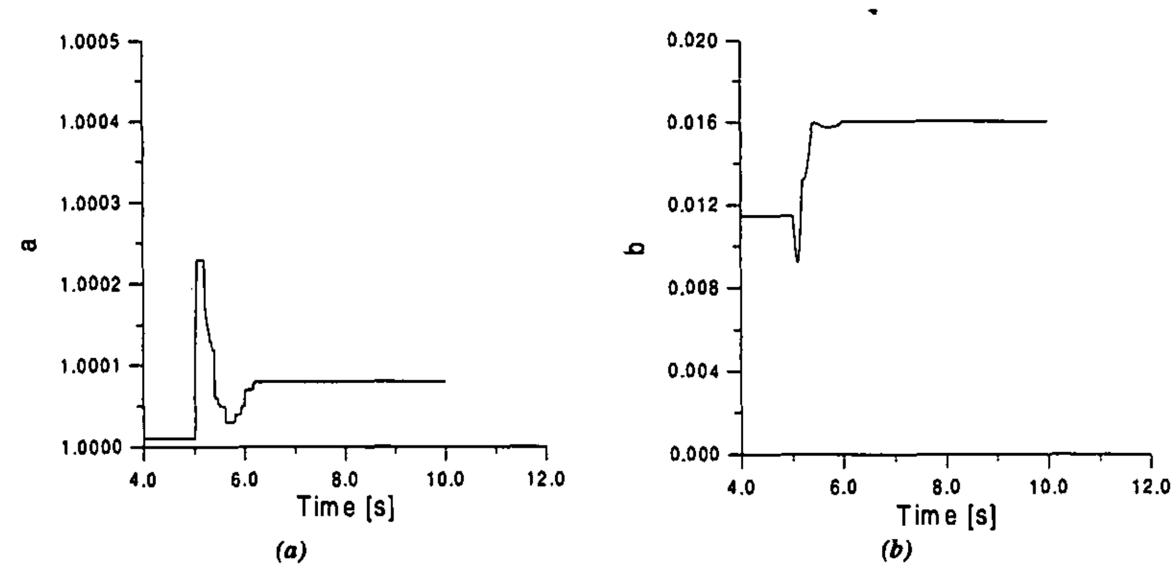
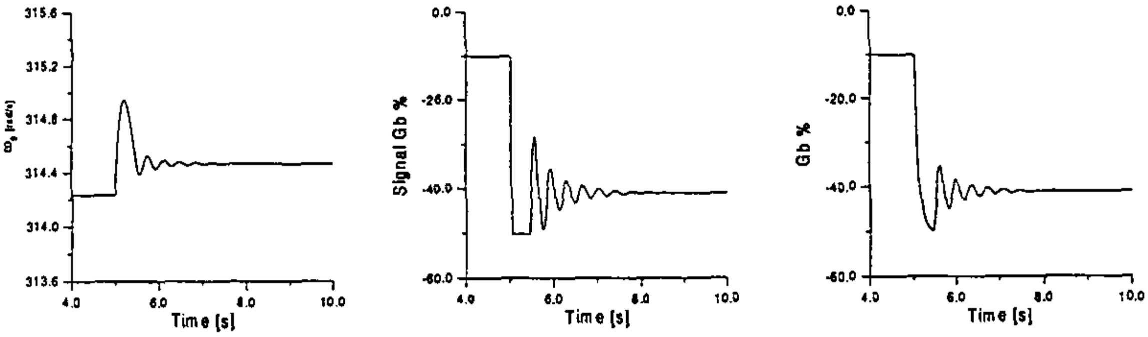
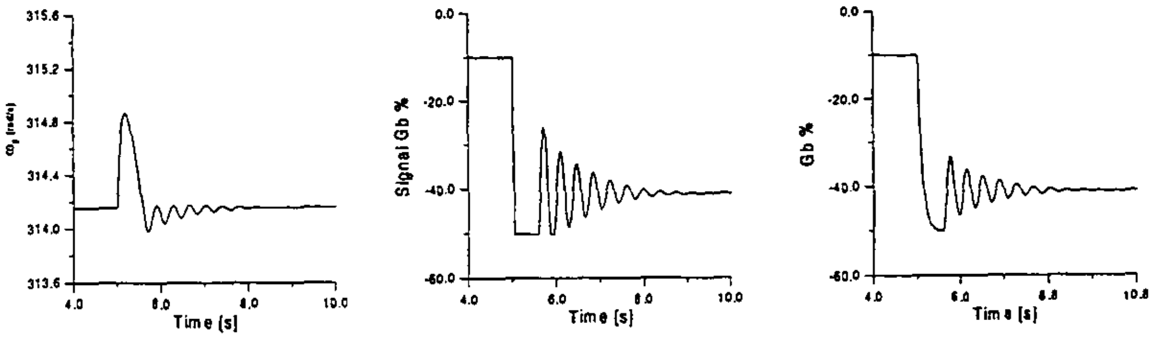


Fig.4 – Estimation of the parameters *a* and *b* of Eq.(8) in the SISO application



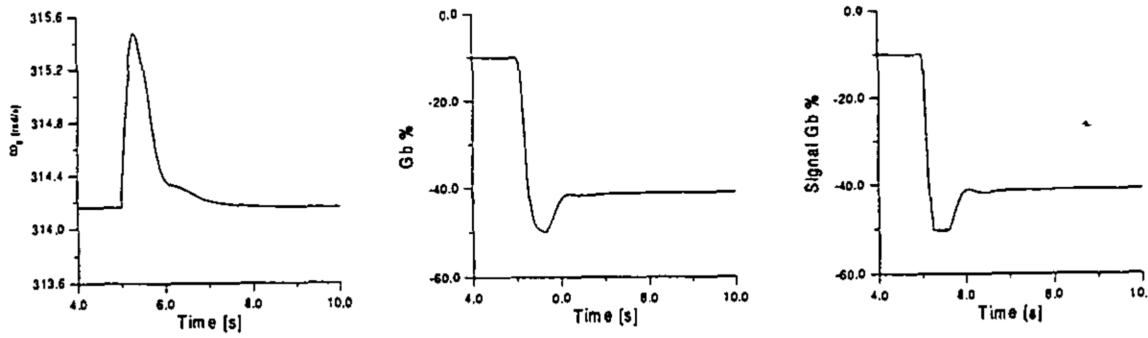
(a) (b) (c)

Fig. 5 – Rotor speed (a), fuel signal (b) and fuel flow (c) for the electric load reduction. OSAA applied to the fuel control.



(a) (b) (c)

Fig. 6– Rotor speed (a), fuel signal (b) and fuel flow (c) for the electric load reduction as in Fig.4 . OSAA applied with integrative correction.



(a) (b) (c)

Fig. 7 – Rotor speed (a), fuel signal (b) and fuel flow (c) to the electric load reduction as in Fig.4 and 5. OSAA applied with integrative correction and limits to the coefficient *b*.

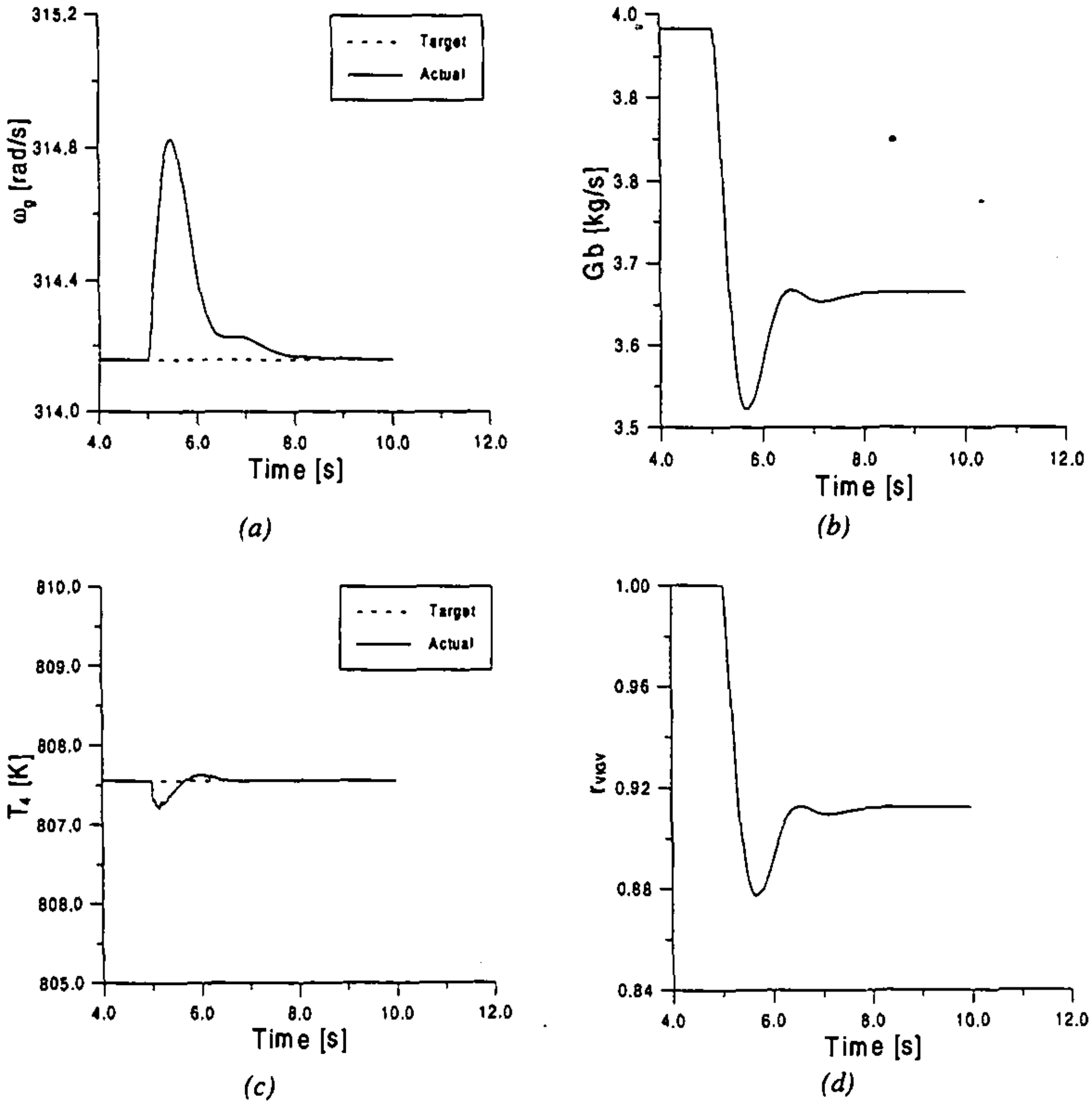


Fig. 8 – Rotational speed (a), fuel flow (b), exhaust gas temperature (c), IGV position (d) response to the electric load variation. OSAA controller in MIMO formulation